From the Sun to Pluto

by Karla B. Clark
Jet Propulsion Laboratory
California Institute of Technology

Abstract

From the Sun to Pluto, all by way of Jupiter. The Outer Planets/Solar Probe (OP/SP) Project first three missions will all visit Jupiter before reaching their destinations of the Sun, the Jupiter moon Europa and the Pluto/Charon system. Using a unique sun shield/high gain antenna Solar Probe will twice encounter the Sun at a distance of three solar radii. Solar Probe will make local measurements of the birth of the solar wind and be able to image surface features as small as 60 kilometers across. The Europa Orbiter mission will send a small spacecraft into the radiation intensive environment around Jupiter and its moon Europa to determine if a water ocean exists below the moon's icy surface. Pluto is the last of the known planets in our solar system left to be locally explored. The Pluto/Kuiper Express will complete this reconnaissance by sending a spacecraft on its long journey to the outer reaches of the solar system.

These technically challenging missions will all require significant technological advances to make them achievable at significantly lower costs when compared to similar previous missions. A core piece of technology which will be common amongst the three missions will be the avionics system being developed under NASA's Advanced Deep Space Systems Development Program (ADSSDP). One of the first deliveries from ADSSDP is the X2000 avionics architecture which includes the main engineering computing system, the attitude control sensors, the power electronics and the core software used to operate the spacecraft in ground test and in flight. The avionics hardware technology utilizes integration of functions among a set of multichip modules with standard interfaces to achieve lower production costs, power and mass. Additionally, the packaging density improvements allow the reduction of the shielding mass required for the survival of the Europa Orbiter electronics within the intense Jupiter radiation belts.

X2000 Introduction

NASA's Advanced Deep Space Systems Development Program (ADSSDP) at the Jet Propulsion Laboratory is developing advanced technology components and systems to enable low-cost, yet ambitious, missions to the outer planets, Mars, and other destinations in the early 21st century. One of the program's products will be a series of engineering development multimission spacecraft systems which we refer to as the X2000 Buses. The X2000 engineering model spacecraft system are to qualify the design and to enable flight units to be procured at a low recurring cost.

The qualification of the First Delivery of the X2000 Bus is currently planned for February 2001. Some of the software development, however, is expected to continue beyond that time. The First Delivery Bus is being designed to perform both the proposed Europa Orbiter mission and the Pluto/Kuiper Express mission with a common build-to-print spacecraft avionics bus. Mission-unique elements, such as science, probes, propulsion modules, and radiation shielding, are being designed modularly with standard, common interfaces to minimize cost.

The avionics, software, and engineering sensors in the First Delivery are also being designed to fulfill the needs of other missions, including New Millennium Deep Space 4/Champollion, Solar Probe, and select spacecraft in the Mars Program mission set. X2000 components and systems would also be available for Discovery missions and Earth orbiting scientific and commercial spacecraft as high-performance components with very low mass and low recurring cost.

OP/SP Mission Set Summary

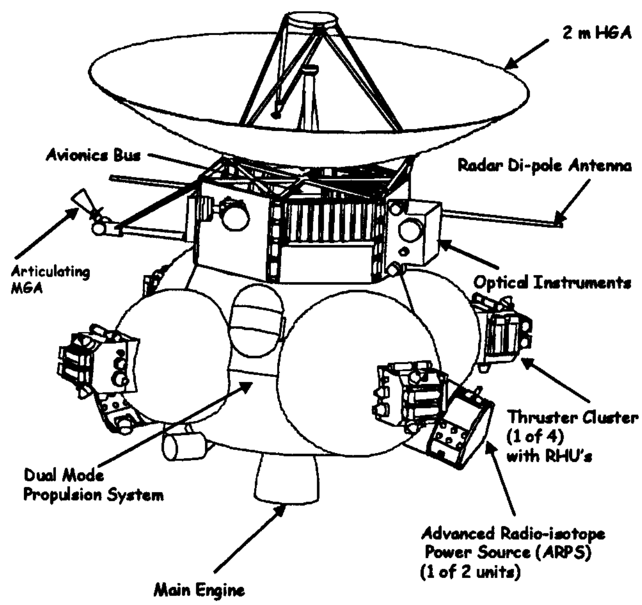
Europa

Jupiter's moon Europa fascinated scientists after the images from the Voyager Mission indicated that the surface of Europa was unusually smooth and lacked visible craters, suggesting that it was very young. Combined with information about its bulk composition, which indicated it had a veneer of water ice, and the knowledge that Europa experienced strong, heat-inducing tides, this finding led to the tantalizing suggestion that a water ocean might be present below the moon's surface. The data were of insufficient resolution to allow much more than theoretical speculation, and the Galileo observations were awaited with eagerness.

The Galileo images did not disappoint. In a June 1996 image, strong evidence appeared for surface cracking into ice floes, reinforcing a Voyager interpretation. Then, the close Europa flybys found the first direct evidence of cryo-volcanism on a Jovian moon. These discoveries were followed by evidence of what appear to be icebergs now apparently frozen into place, but which seem to have been floating on some substrate that is difficult to conceive of as anything but liquid. But while increasingly compelling, there was as yet no unequivocal determination of the existence of a global ocean on Europa or its size.

About the time of these discoveries, the Jet Propulsion Laboratory began advanced studies of a mission called the Europa Orbiter which would determine if an ocean is present and the thickness of the overlaying ice layer. If a thin ice layer could be confirmed, future spacecraft could be designed to penetrate the ice and look beneath its surface.

Figure 1: Europa Orbiter Spacecraft



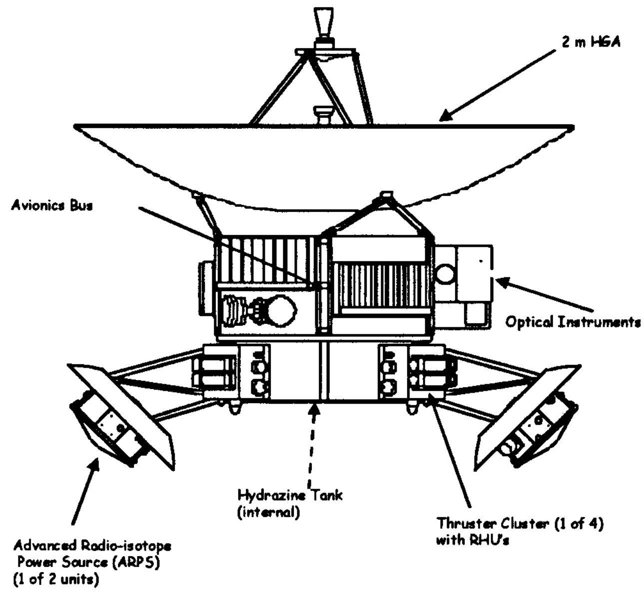
Data from Galileo and IUE indicate that materials other than ice, including sulphur, are present on the surface of Europa. Over time, these materials could conceivably be churned into the water/ice below. It is this material (probably including organics), the presence of water, and the tidally driven internal heat source that intrigue scientists who speculate on the possibility of life in the oceans of Europa.

The current design for the Europa Orbiter (see Figure 1) would take about 3 to 4 years to reach the Jovian system and an additional 1½ to 2 years to reach orbit around Europa. The mission consists of one month in orbit around the moon taking data and relaying the data back to Earth. The mission duration is driven primarily by the intense total ionizing dose radiation levels present in the Jovian system. Even with the short lifetime, the mission is scientifically engaging and rich and would lay the groundwork for future missions to Europa and other Jovian moons such as Io.

For the Europa mission, the X2000 First Delivery avionics bus will be interfaced with a 750 kg wet mass dual-mode bipropellant propulsion module. This will provide for attitude control, Trajectory Correction Maneuvers (TCM's), Jupiter Orbit Insertion (JOI), and Europa Orbit Insertion.

One proposed Europa science suite features a radar sounder to remotely determine the depth of the surface ice and determine if a liquid water ocean exists beneath it. Visible and thermal imaging is also included to map the surface and determine composition and structure. Accurate tracking of the spacecraft orbit, in conjunction with a laser altimeter, will be used to determine the tidal flexing of Europa and provide key information on the internal structure and nature of possible subsurface oceans.

Figure 2: Pluto/Kuiper Express Spacecraft



Pluto

Pluto is the only planet in our Solar System which has not been explored by a spacecraft. Pluto and its large moon Charon form a binary system that has an orbit varying dramatically in distance from the Sun. Currently, Pluto's orbit is within the orbit of Neptune, but 124 years hence it will be outside Neptune's orbit at an aphelion of 49 AU. This variation in distance will cause Pluto's atmosphere to sublimate (or condense) so that it will become increasingly more difficult to detect or utilize for science or aerobraking.

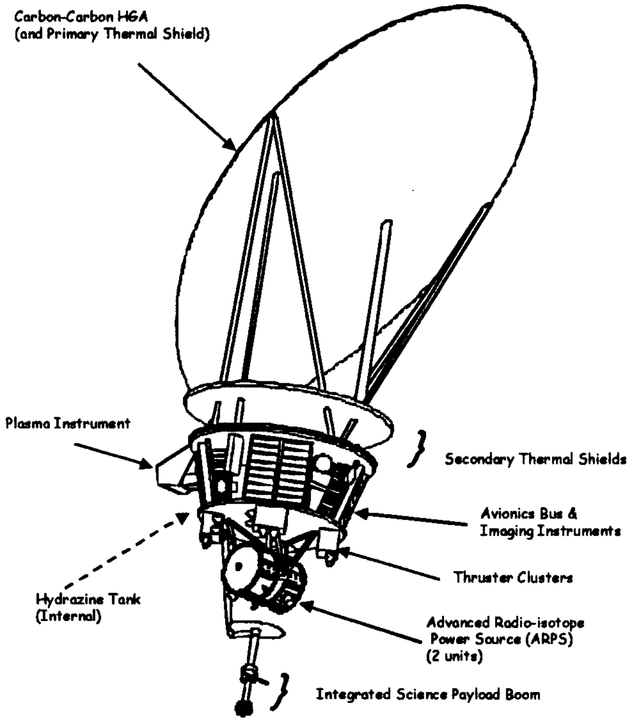
Even with the long flight times of 9 to 10 years, the Pluto/Kuiper Express mission is designed to reach Pluto/Charon while there is still a significant atmosphere. It is unknown when, or even if, the atmosphere will "collapse". It may just gradually diminish. There are conflicting opinions, all based on the same very limited data. Characterization of the Pluto/Charon system will help answer questions about this unusual binary system and will contribute to our understanding of the formation of our Solar System.

After a fast reconnaissance flyby of the binary system, the trajectory will be altered to fly by a member of a group of objects referred to as the Kuiper Disk Objects. Kuiper Objects, predicted in the late 1940s by Edgeworth and Kuiper, were only discovered in the early 1990s yet now there are several dozen of these objects catalogued. These small objects form a disk around our solar system and are believed to be remnants of the solar system's formation and to be the primary source of short period comets. By studying at least one of these objects, scientists hope to learn more about the possible origin of the volatiles that form the Earth's atmosphere and oceans.

The extreme distance from the Sun, long lifetime, and fast flyby speed make this a very challenging engineering mission, as well as an exciting science mission. The Pluto/Kuiper Express spacecraft is depicted in Figure 2.

For Pluto/Kuiper Express, the X2000 First Delivery bus will be mated with a 35 kg wet mass hydrazine monopropellant propulsion

Figure 3: Solar Probe Encounter Configuration



module. The propulsion module will provide for attitude control, TCMs, a probe deflection maneuver at Pluto, and retargeting to Kuiper disk objects. The propulsion module is also designed to structurally support an experimental microspacecraft probe that would be separated from the main spacecraft and targeted to conduct atmospheric science.

Solar Probe

Solar Probe is an exploratory mission to our star which gives us life and whose effects on the earth and solar system are profound. We are only beginning to understand the relationship between the sun, its atmosphere (the corona), and the solar effects on the earth. The recent observatory missions (YOHKOH and SOHO) have given us new data to answer old questions and create new questions that only the Solar Probe can answer. The mission is designed to take scientific instruments into the solar atmosphere to within 3 solar radii (2.1 Gm) of the Sun's atmosphere where they will make measurements to determine what causes the heating of coronal particles (to well over a million degrees), as well as what are the sources and acceleration mechanisms in the solar winds. The low-altitude passes of the Solar Probe spacecraft over the polar regions will allow imaging that has here-to-fore been impossible and at perspectives that will never be attained from near-Earth observatories.

This close approach to the Sun requires that several technical challenges be undertaken. Materials in the exposed portions of the spacecraft must survive the extreme temperatures during the encounter with the Sun. An integral heat shield and high-gain antenna design has been developed to shield the spacecraft from the extreme heating while providing high-rate, real-time communication with the Earth during the critical solar encounter period (see Figure 3).

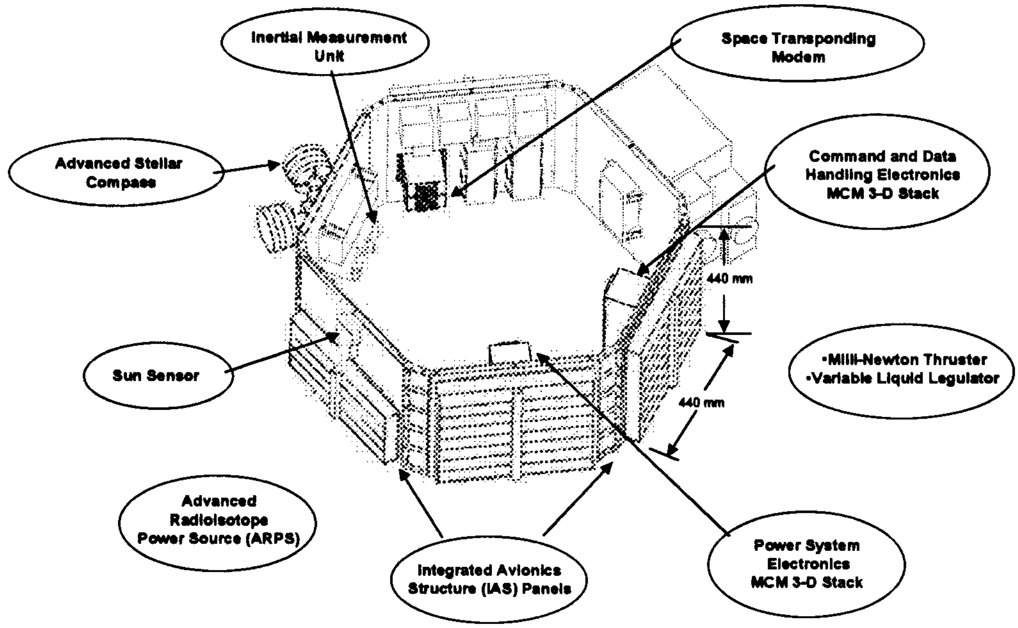
This innovative concept is accomplished through the unique trajectory and a new application of high temperature materials technologies. The trajectory uses a Jupiter gravity assist maneuver to provide the unique quadrature geometry at perihelion that enables the shield/antenna combination.

A complex set of power sources, including multiple solar arrays and batteries, is required to survive the extremes in solar radiance between the dim cold of a Jupiter gravity assist flyby and the intense heating of a close encounter with the Sun.

Because of the unique shield geometry and thermal requirements of the mission, the X2000 First Delivery bus cannot be used "as is". The core avionics will be similar, if not identical to hose used on Pluto/Kuiper Express but physically there has to be some tailoring. The slices will be mounted on custom designed panels designed specially for Solar Probe. Most of the core software from the First Delivery bus will also be utilized.

The propulsion requirements for Solar Probe are very similar to Pluto Express;

Figure 4: Europa Orbiter Spacecraft



therefore, Solar Probe may use the same tankage and components at a recurring cost. The Propulsion Module integration structure for Solar Probe will be different from Pluto Express, however, due to the unique shield geometry and thermal constraints.

X2000 First Delivery Bus

A concept of the First Delivery spacecraft bus configured for the Europa Orbiter is shown in Figure 4.

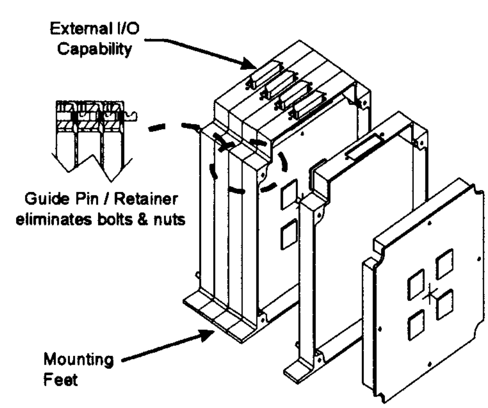
Microelectronics

To accommodate the diverse requirements of the multiple missions identified above, the architecture of the X2000 First Delivery microelectronics must be scaleable. This requirement has a number of implications, one of which is the need for standard interfaces. This will allow modules to be added or removed from the system to meet the requirements (performance, mass, power, volume) of a specific mission.

The microelectronics are a highly integrated stack of standard sized (10 x 10 cm) Multi-Chip Modules (MCMs) and Chip-On-Board (COB) subassemblies. Both of these technologies utilize unpackaged bare microchip die directly bonded onto a standard size substrate. The substrate contains all the printed circuit traces required for electrically connecting the die together. At the periphery of each of these subassemblies are all of the electrical terminals required to interface the subassembly with other elements of the spacecraft. These subassemblies are often referred to as "slices."

The slices are stacked on top of one another using a new packaging technology that allows different combinations of MCMs and COBs, or even conventional PC boards, to be assembled together in any order, with the electrical terminals on the periphery in contact with those of the adjacent slices (Figure 5).

Figure 5: X2000 Micro-Electronics Packaging



There are standard terminal locations for data buses, power buses, and other signals, so that these can be reconfigured in a plug and play fashion. To change between single-string and dual-string configurations requires only the removal or addition of slices. In the same manner, more memory or processors can be added, or individual slices can be upgraded to the next generation simply by replacing those slices with the new ones, leaving the remainder of the slices in the stack unchanged.

The performance of the system must not be affected by the addition or removal of modules. As the number of modules increase, the system should not degrade. This is achieved with a multi-master bus, avoiding the performance bottleneck that might occur with a dedicated master. Each module in this architecture is individually coupled to the bus and has its own resources.

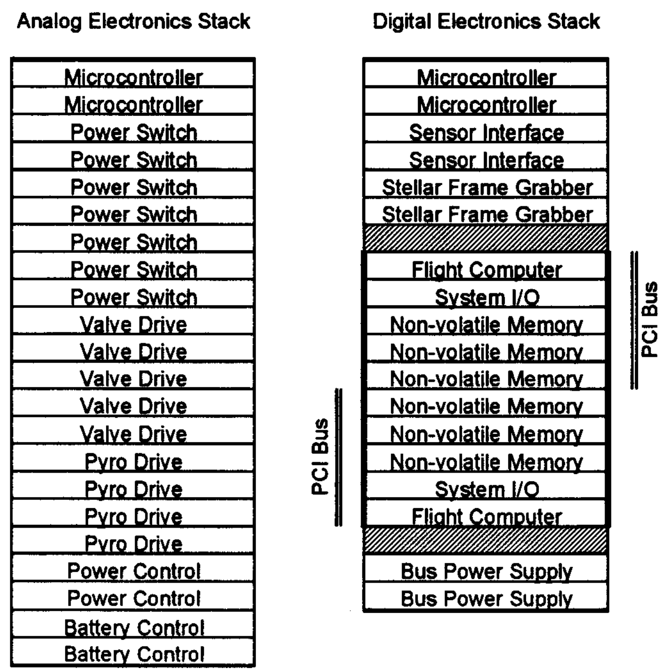
In the X2000 architecture, the role of the flight computers is flexible and scaleable, allowing the number of processors to be increased or decreased depending on mission requirements. It also allows the system to be more fault tolerant, so that if one computer fails, another can take over its tasks.

Figure 6 shows a typical configuration which could be utilized for the Europa and Pluto missions. Although there are 39 total slices in this configuration, they are built up from only 10 different types of slices that must be designed and qualified. The radiation shielding is also modular and tailored to the requirements of each mission.

Software and Autonomy

From the software's point of view, the microelectronics stack resembles a local area network, with multiple processors running standard operating systems and languages that communicate over high bandwidth interconnections. Each processor (flight computers and microcontrollers) will run a commercial real-time network-aware operating system. The software will be distributed, multi-threaded, and object oriented.

Figure 6: Dual-String Micro-Electronics Stacks



Telecommunications

The communication system for each spacecraft consists of a high gain antenna, solid state power amplifier and Space Transponding Modem. The communication is performed via an X-band link between the spacecraft and the Deep Space Network (DSN). The unique trajectory of the Solar Probe will allow real-time data transfer during first sun encounter. The other two missions, and the second pass of the Solar Probe, will utilize the on-board memory for data storage until the data can be relayed back to Earth.

Sensors and Attitude Control

The temperature sensors are plugged into the spacecraft using a standard I^2C low-to-moderate data rate sensor bus. The Inertial Measurement Units (IMUs) and the star tracker plug into the 1394 bus, provided for all the spacecraft components. The specific attitude control sensors for these missions have not yet been chosen. Obviously, for the Europa raditation environment, non-recurring development will be necessary to achieve low mass solutions to this tough requirement. Pluto/Kuiper Express and Solar Probe may be able to use commercially available low mass sensors.

Bus Structural and Thermal Design

The baseline bus design for Europa Orbiter and Pluto/Kuiper Express is shown in Figure 4. Six rectangular composite honeycomb panels attach to a lightweight titanium frame to form a stiff cubical structure to which components are mounted internally and externally. The panels are modular and can be independently removed for access and service. The exact configuration of the avionics on each panel will depend on the numbers of each slice required to perform the mission. Due to volume constraints formed by maintaining the majority of the spacecraft within the umbra of the high gain antenna (or in the shade) during closest approach to the sun, Solar probe utilizes a 4 panel configuration with science instrument filling gaps between the panels.

The internal portion of the bus is maintained at a temperature range of -30 to 0°C. Heat is obtained both from the operating electronics and thermal communication with the attached propulsion module, which in the case of Pluto Express and Europa Orbiter is warmed with waste heat from an attached Radioisotope Power Source (RPS). Radiative heat loss from the bus is controlled by thermal blankets, and thermostatically controlled louvers on one of the bus panels correct for variations in the heat loads inside the bus.

Propulsion Modules

The baseline propulsion subsystem for Europa Orbiter is a dual mode bi-propellant system designed to approximately 2600 m/s of Delta V capability. The Pluto/Kuiper Express and Solar Probe missions only required small amounts of Delta V and thus are using monopropellant systems. Small milli-newton thrusters are being developed to help reduce the amount of propellant required for Europa Orbiter and Pluto/Kuiper Express while still meeting the accurate pointing requirements.

Power Sources

All three Outer Planet/Solar Probe missions are being designed to be powered by RPS. The avionics bus is designed to include a battery and charge control electronics. The battery is used for brief periods where power consumption must exceed the output of the RPS, mainly during propulsion maneuvers and communication to earth.

MISSION DATA SYSTEM

In past JPL deep space missions, there have been four distinct data systems: the testbed system, the flight software on-board the spacecraft, the uplink system, and the telemetry and archiving system (the latter two often called the Ground Data System, but they are in fact two distinct streams of subsystems that cannot communicate electronically). The future JPL software system instead embodies a new concept of a single Mission Data System (MDS) which is a collection of end-to-end services, and is used throughout the life cycle of the mission, through design, development, integration and test, operations, and archiving. This MDS is being pioneered by X2000 First Delivery but will continue to develop well past the intitial launches of the Outer Planets/Solar probe missions. Mission Unque software will be written using the X2000 core capbailities to form the mission unique Data System.

End-to-end services means that a subsystem (e.g., a spacecraft battery) provides device driver flight software, tactical goal-oriented flight software (e.g., charge battery), strategic goal-oriented flight software (e.g., achieve and maintain maximum charge prior to orbit insertion), planning models for the planner (same planner on-board as on-ground as for system engineering scenarios), performance analysis based on telemetry, and commanding. This is, in fact, no increase in scope for the project: because all these tasks already need to be done for each subsystem. The difference is that now a subsystem is responsible, and empowered, to provide a complete plug-and-play package.

CONCLUSIONS

The Outer Planets/Solar Probe missions are three very scientifically diverse missions going to the extremes of the solar system. One will brave the extreme heat of the sun, while another explores the vast coldness of Pluto's orbit while the third will encounter deadly radiation doses in the Galilean System. The avionics for these three distinct spacecraft will be alike in every way possible to reduce the recurring costs for entire project. Sate-of-the-art avionics are required to meet the performance and mass requirements for the set of missions. The X2000 First Delivery avionic set is pushing the state of the art in achieving a highly integrated, yet modular and scaleable, spacecraft architecture that will have high performance capabilities, yet very low mass.

The software for the avionics is being written to accommodate all the Outer Planets/ Solar Probe missions as well as form the core for all future JPL missions. The MDS presents daunting challenges in management and in technical execution, requiring considerable sophistication. It is probably not cost effective to replace all the legacy systems that have evolved over decades. It is also not reasonable to expect that the technology developed for the First Delivery will not become obsolete with time. Therefore, the Mission Data System will include legacy code whose implementation may be obsolete but whose function is still vital, new state-of-the-art code, and code that is yet to be imagined which will be implemented with whatever comes after.

ACKNOWLEDGMENTS

Many people on the X2000 and Outer Planets/Solar Probe Project Teams contributed to the work described herein and provided assistance to this publication.

The work described in this paper was performed at the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.

Author Biography:

Karla B. Clark is the Program Engineer for the Outer Planets/Solar Probe Project. She has worked on flight spacecraft since joining JPL 11 years ago. She has been involved with such programs as Mars Observer, TOPEX, Mars Global Surveryor and most recently Cassini. Karla was also a Group Supervisor for the Power Systems and Electronics Group in the Avionics Equipment Section for 3 ½ years.